Variability In Solar Flux At The Ocean Surface: Direct and Indirect Effects, and Positive and Negative Feedbacks

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> *"Since we are the children of the sun and our bodies a product of its rays… it is a worthy problem to learn how things earthly depend on this material ruler of our days"* (S. P. Langley, 1898).

Most life on Earth depends directly or indirectly on the solar radiation reaching the Earth's surface. However, there is much that we do not understand about the variability in the solar flux and how it affects Earth's climate, the biota, and biogeochemical cycles. The problem we address, therefore, is how the nature of the variability in solar flux stabilizes, or amplifies variability on Earth, particularly in regards to Earth's biota. Also, variability that originates on Earth (e.g., aerosol production and surface albedo changes) can have unforeseen consequences in causing variability in the solar flux at the Earth's surface, and this component of the Earth-sun relationship needs to be understood. Our research corresponds to Strategic Focus Roadmap Areas #8 (Explore the dynamic Earth system to understand how it is changing, to determine the consequences for life on Earth, and to inform our search for life beyond) and #9 (Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers).

While much attention has been paid to the sun's influence on thermal forcing and climate change, (for example through Milankovitch cycles and glaciations) not nearly as much is known about the effects of changes in the visible wavelengths on photosynthesis by organisms in the terrestrial and oceanic realms, the complex interaction between these changes, and the biotic response. Similarly, while much attention has been paid to the effect of anthropogenic forcing on greenhouse warming, less is known about the effect of anthropogenic forcing on the quality and quantity of light reaching the Earth's surface, and in turn, the effect this has on photosynthetic organisms and evapo-transpiration. (The only exception is the studies done on the effect of excessive ultraviolet (UV) radiation on biota caused by the ozone hole.)

Aerosols in the atmosphere influence productivity of the biosphere both by changing the spectral quality and quantity of light reaching the Earth's surface as well as through addition of micro- and macronutrients. However, it is not yet known if the influence is positive or negative (it can be both, depending on the region). For example, aerosols that selectively absorb UV radiation may enhance primary productivity at the ocean surface. On the other hand, a net reduction in downwelling photosynthetically active radiation (PAR) due to absorbing aerosols will reduce productivity. Dust storms that blow across the ocean from Africa can reduce downwelling PAR by as much as 50% on given days. But these same dust storms transport iron, a critical micronutrient, which would have a positive effect on productivity.

The sun's irradiance varies over an 11-year cycle by 1 W m^{-2}. Volcanic activity injects aerosols into the stratosphere that can cause a negative forcing. For example, the eruption of Mount Pinatubo in 1991 caused a reduction of solar flux of about 3 W m^{-2} in the first year. Even though the solar flux declined, the diffuse portion increased, so that over the following 2 years, terrestrial photosynthesis actually increased. The effect of diffuse solar radiation on oceanic photosynthesis is unknown.

Human activity has increased aerosols in the atmosphere by an order of magnitude compared to the 11-year solar cycle and the Pinatubo eruption, but the net effect of this increase on productivity of the oceans is not known. We do not even know the sign of this impact – i.e. if the productivity is enhanced or reduced by the increase in anthropogenic aerosols. There are three important types of anthropogenic aerosols – sulfates, organic aerosols, nitrate, and soil dust. Soil dust aerosols, although they are naturally occurring material, are often produced when the soil or vegetation is disturbed by human activity. Thus changes in land use practices can change the amount of soil aerosol produced. Organic aerosols are produced during combustion of biomass and fossil fuels (soot). Black carbon is also a byproduct of these practices and both organic aerosols and black carbon absorb visible radiation reducing photosynthetically active radiation reaching the ocean surface. Sulfates are released as SO_2 during combustion of fossil fuels and are oxidized in the atmosphere to become sulfuric acid. Apart from playing an important absorbing and scattering roles in the atmosphere, sulfates could also promote atmospheric processing of other aerosols to make them labile for biological activity. The important role of the biota as emitters of gases that form aerosols has also not been addressed. These aerosols can act as condensation nuclei and influence cloud formation.

In the foregoing, we have outlined some of the processes whereby the solar flux has both direct and indirect effect on biogeochemical cycles on Earth, climate, and on terrestrial and ocean productivity. The kinds of feedbacks these effects create are little understood, but need to be established to be able to forecast the state of the Earth in future. Over geologic time, the solar flux has varied by relatively small amounts, yet these small changes somehow have been amplified to produce the major climate cycles over the last several hundred thousand years. We need to figure out the mechanisms by which the amplification occurs, but using observations and technology available at present, and expected to be available in the near future. Indirect effects, unlike direct effects, as we have noted above, may become seen as negative or positive feedbacks. It may be that amplification of the effects of solar flux occurs over long time scales, whereas, more direct effects are measured over short time scales. Further, it may be that the effects are observed more clearly in polar regions than they are in lower latitudes.